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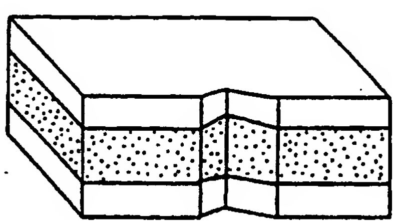

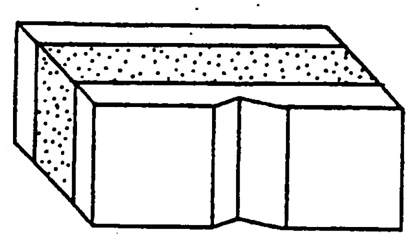

(57) Abstract

A metal matrix composite comprising a stack of alternate layers of unreinforced metal and discontinuously reinforced metal. In a preferred embodiment, the unreinforced metal is an aluminum alloy and the discontinuously reinforced metal is an aluminum alloy reinforced with silicon carbide particles. The metal matrix composite may be formed by the steps of: (a) providing a stack of layers unreinforced metal and discontinuously reinforced metal; and (b) applying sufficient heat and pressure to the stack to cause interlayer adhesion of the layers and thus form a laminated MMC. The stack of layers may be alternating layers of unreinforced metal and discontinuously reinforced metal. In a preferred embodiment the outer layers of the stack are an unreinforced aluminum alloy.

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METAL MATRIX COMPOSITE HAVING ENHANCED TOUGHNESS AND METHOD OF MAKING

This invention relates to metal matrix composites (MMCs) and the manufacture thereof. More particularly, the invention relates to methods for increasing the fracture toughness of metal matrix composites via the fabrication of discontinuously reinforced laminate structures.

Metal matrix composites have received much attention as a means to produce products having improved properties. However, while significant gains may be made with respect to certain properties, sometimes these are obtained at the expense of other properties. For example, in the aluminum industry it is known that the yield strength and modulus of elasticity of an aluminum alloy can be increased through the use of discontinuous reinforcement additions to form discontinuously reinforced aluminum (DRA) materials. Nevertheless, commensurate improvement in fracture toughness is not obtained in such MMCs. For this reason the improvement in other properties may be unusable in components for which toughness is important.

Thus it can be seen that it would be of great advantage, particularly in aluminum

alloys, if the yield strength, modulus of elasticity and fracture toughness can be improved together. The present invention permits these properties of a metal alloy to be enhanced. That is, the present invention provides MMCs having improvements in modulus of elasticity while maintaining or improving fracture toughness.

The primary object of the present invention is to improve the toughness of a metal matrix composite.

Another object of the present invention is to improve the fracture toughness of a metal matrix composite without significantly decreasing the yield strength or modulus of elasticity.

Another object of the present invention is to improve the toughness of a metal matrix composite formed from alloys of aluminum, titanium, steel or combinations thereof.

Accordingly, there is disclosed a metal matrix composite having improved fracture toughness. The metal matrix composite comprises a stack of alternate layers of unreinforced metal and discontinuously reinforced metal. In a preferred embodiment, the unreinforced metal is an aluminum alloy and the discontinuously reinforced metal is an aluminum alloy reinforced with silicon carbide particles.

A second embodiment of the invention is a method for providing a metal matrix composite having improved fracture toughness. The method comprises the steps of: (a) providing a stack of layers of unreinforced metal and discontinuously reinforced metal; and (b) applying sufficient pressure to the stack to cause interlayer adhesion of the layers and thus

form a laminated MMC. The stack of layers may be alternating layers of unreinforced metal and discontinuously reinforced metal. It is preferred that the unreinforced alloy forms the outer layers of the laminate.

In a preferred embodiment, the method comprises the steps of: (a) providing a stack of alternating layers of an unreinforced aluminum alloy and aluminum alloy reinforced with silicon carbide particulates; (b) heating the stack and (c) applying sufficient pressure to the stack to cause interlayer adhesion. Afterwards, the stack may be solution heat treated and/or artificially aged. In a most preferred embodiment, metal foil is placed between the layers to enhance interlayer adhesion.

Other features of the present invention will be further described or rendered obvious in the following related description of the preferred embodiment which is to be considered together with the accompanying drawings wherein like figures refer to like parts and further wherein:

Figure 1 is a photomicrograph of an aluminum alloy product made in accordance with the invention. The laminate has been tested and illustrates crack tip blunting and interface delamination which resulted from impact testing.

Figure 2 is an illustration of laminates of present invention in the crack divider and crack arrestor orientations.

The terms "unreinforced metal" is used herein to refer to metals and alloys containing less than 5 vol.% of non-metallic added reinforcement materials and preferably less than 1 vol.%. Examples of unreinforced metals

include aluminum, titanium, magnesium, iron, copper, zinc and alloys in which at least one of these metals is the largest single component.

The term "reinforced metal" and "reinforced alloy" are used interchangeably herein to refer to alloys containing more than 5 vol.% of non-metallic added reinforcement materials. Examples of reinforced metals include unreinforced metal to which fibers, whiskers, filaments, particles, ribbon, wire, flake, crystals, platelets and other non-metallic reinforcements are intentionally added. The term is not intended to include metals which contain only intermetallics except where the volume or type of such intermetallics provides significantly increased elastic modulus.

The term "discontinuously reinforced metal" and specifically "discontinuously reinforced aluminum" (DRA) are used interchangeably herein to refer to metals and alloys in which the morphology of the reinforcement is discontinuous, most often with a ratio of largest to smallest dimension of less than about ten to one. The term is not intended to include alloys reinforced with long fibers, ribbons, or whiskers with a ratio of largest to smallest dimension of more than about ten to one.

The term "composite" is used herein to refer to a material in which two or more constituents are combined to result in a material which has properties significantly different from either consituent. Reinforced metal, reinforced alloy, discontinuously reinforced metal and discontinuously reinforced aluminum are examples of metal matrix composites. Typical composites are materials in

which one of the components has very high strength, modulus or both and the other has high ductility. Some of their properties generally follow the rule of mixtures. For example, if elastic modulus is the property of interest, the elastic modulus of the composite is approximately the weighted sum of the elastic moduli of the constituents.

The term "intermetallic" is used herein to refer to a phase formed in-situ as a result of chemical and thermodynamic interactions. Intermetallics may have a reinforcing effect. However as stated above, the term "reinforcing material" is not generally intended to include intermetallics.

The terms "toughness" and "fracture toughness" are used interchangeably herein to refer to the ability of a material to resist catastrophic growth of a crack.

The term "laminated" is used herein to refer to a layered structure having at least two layers with dissimilar properties.

The term "foil" is used herein to refer to metal which has been formed into a layer having a thickness of less than about 0.15 mm (0.006 inches). Foil is commonly a rolled product having a rectangular cross section.

The term "sheet" is used herein to refer to metal which has been formed into a layer having a thickness greater than about 0.15 mm (0.006 inches) and less than about 6.325 mm (0.249 inches). Sheet is commonly a rolled product having a rectangular cross section.

The term "plate" is used herein to refer to metal which has been formed into a layer having a thickness greater than about 6.325 mm (0.249 inches). Plate is commonly a

rolled product having a rectangular cross section.

By reference to Figure 1, there is shown an enlarged cross-section of an aluminum alloy product produced in accordance with the present invention. A section of DRA (lighter color layer) is sandwiched between two layers of unreinforced alloy. The laminate alloy product of the invention has beneficial properties resulting from both types of layers.

Powder metallurgy may be used to obtain the alloys laminated to form the composite structure of the present invention. The same alloy may be used in both the unreinforced and reinforced layers or one layer may be comprised of a different alloy, depending to some extent on the properties desired in the final product. It is preferred that in the reinforcement layers, the reinforcement material be uniformly distributed throughout the product in order to provide the optimum combination of strength, toughness and fatique resistance.

In making product from aluminum alloy powder, a base aluminum powder alloy such as AA X2080, 6113 or X7093 is selected depending on the basic properties desired. For example, powder metallurgy alloy X7093 exhibits higher levels of strength and toughness than conventional alloys such as 7075 and 7050. Further, the base aluminum powder alloy can be selected to produce a fine grain structure. Generally, the base aluminum powder should have a particle size in the range of -200 to -325 mesh (Fisher sub-sieve sizing screen).

Unreinforced aluminum alloys have capability for good strength and fracture toughness but their elastic modulus is

considered to be less than desirable for stiffness critical applications. The addition of reinforcement materials, such as particles of silicon carbide (SiC) to the alloy powder, serves to enhance the elastic modulus with respect to the unreinforced matrix alloy. As noted above, the incorporation of reinforcement particles degrades fracture related properties such as ductility and fracture toughness. Surprisingly, the combination of layers of unreinforced and reinforced layers produce a material having combined improvements in modulus of elasticity while maintaining improved toughness.

As seen in Figure 1, the reinforcement material provides a mechanism for crack deflection. Although not wishing to be bound by any theory, it is believed that the fracture toughness of the laminate is increased through the mechanisms of crack blunting and crack front deflection. Crack blunting involves impeding crack growth. Crack front deflection increases the area in which fracture-related events occur and therefor increase the energy absorption capability of the material.

The amount of reinforcement material can range from a very small amount to a rather significant amount if it is desired to greatly improve elastic modulus. Typically, the reinforced layers or regions are formed from a blend comprising at least 5 vol.% of the reinforcement constituent with preferred amounts being at least 10 to 30 vol.%. Normally, the blend should not comprise more than 55 vol.%.

The base powder alloy and the reinforcement are mixed to provide a blend wherein the reinforcement material is

substantially uniformly distributed throughout it. Thereafter, the blend can be compressed to form a compact.

The compact can be subjected to a vacuum preheat for purposes of degassing. Typically, for aluminum, the preheat is carried out at a temperature in the range of 800° to 1100°F. Thereafter, it may be hot pressed to provide up to 100% density. For aluminum powder, the compact can be hot pressed at a temperature in the range of 800° to 1100°F., and pressing can be carried out at pressures in the range of 30,000 to 90,000 psi.

As well as providing the alloy with controlled amounts of alloying elements as described hereinabove, it is preferred that the alloy be prepared according to specific method steps in order to provide the most desirable characteristics. Thus, the alloy described herein can be provided as an ingot or billet for fabrication into a suitable wrought product by techniques currently employed in the art. The ingot or billet may be preliminarily worked or shaped to provide suitable stock for subsequent working operations.

The reinforced metal can be rolled or extruded or otherwise subjected to working operations to produce stock such as sheet, plate or extrusions or other stock suitable for shaping into the end product. Typically extruding, for example, of the hot pressed compact, should be performed at a temperature in the range of 550° to 900°F. depending on the composition of the alloy.

The reinforced metal sheet or plate is then stacked in alternating layers with unreinforced metal. A layer of metallic

foil may be placed between the layers to increase the interlayer adherence. The stack is then roll bonded to produce a unreinforced laminate having alternating layers or strata of unreinforced and reinforced material.

The resulting laminate can then be formed or worked to the desired product, various thermal operations may be required to obtain the proper metallurgical condition in the metal. In the case of precipitation-hardened alloys, a solution heat treatment is used to substantially dissolve soluble elements. The solution heat treatment is preferably accomplished at a temperature in the range of 800 to 1100°F. and typically at about 900°F. for about 1 hour.

Solution heat treatments can range from several minutes to about 2 hours or more at the solution heat treating temperature. Extending the solution heat treatment time beyond about 2 hours generally does not provide further improvements in final properties.

To further improve the properties necessary to the final product, alloys which are solution heat treated should be rapidly quenched to prevent or minimize uncontrolled precipitation of various phases which, when improperly formed, can degrade properties. A cold water quench is preferred. Thus, it is preferred in the practice of the invention that the quenching rate be at least 10°F./sec with a preferred quench rate being at least 100°F./sec.

The product can be artificially aged. This may be accomplished by subjecting the product to a temperature in the range of about 200° to 400°F. for a sufficient period of time to provide the desired yield strength. The period for artificial aging can run from several

minutes to many hours. For some alloys such as 7XXX series alloys, artificial aging is accomplished by subjecting the product to a temperature in the range of 250° to 325°F. for a period of at least 16 hours.

While reference herein has been made to using aluminum powder alloy products, it should be understood that metal other than aluminum alloys may be combined with the intent of increasing the fracture resistance of the final products. Such materials can include, for example, metals such as steel and titanium or other materials having properties desirable in the final product.

While the invention has been described in part with respect to powder metallurgy, its application is not necessarily limited thereto. That is, the present invention discloses a metal or alloy structure having a dual or duplex structure comprised of alternating strata of unreinforced and reinforced metal wherein the strata act in combination to improve the toughness, strength and fracture resistance of the structure.

The following examples are offered to illustrate the advantages of the present invention. The X7093 powdered alloy used in the Examples is commercially available from The Aluminum Company of America (Alcoa). The SiC reinforcement material used in the Examples is F-600 grade SiC which is commercially available from Norton Company.

<u>Example 1 (Prior Art)</u>

A batch of powdered aluminum alloy, X7093 was cold isostatically compacted into a cylindrical mold to 70-80 % of theoretical density. The cylindrical mold was sealed,

degassed and hot pressed at 900°F. to produce a 100% density billet. Thereafter, the billet was extruded at 850°F. The elastic modulus, yield strength (YS) and strain at failure were then measured and recorded on Table 1.

Charpy impact tests were performed on notched and unnotched samples of the material of Example 1 and the results are recorded on Tables 2 and 3.

Table 1

Example	Material	Elastic Modulus*	0.2% Offset YS	Strain At Failure (%)
1	X7093	64.8	573	13
2	X7093/ 15.wt.% SiC	98.6	615	4
3	roll bonded laminate	87.9	582	10
4	roll bonded laminate with foil	79.4	-	-
5	adhesive bonded laminate	75.5	575	-

* GPa

Example 2 (Prior Art)

A batch of the powdered aluminum alloy used in Example 1 is mixed with 15 vol.% silicon carbide particles to produce a uniform blend. The blend was then processed as in Example 1. The elastic modulus, yield strength (YS) and strain at failure were then measured and recorded on Table 1. As can be seen in Table 1, the reinforced material of Example 2 exhibited a 52% increase in modulus of elasticity over the material of Example 1 and the yield strength remained about the same (7% increase).

Charpy impact tests were performed on

notched and unnotched samples of the material of Example 1 and the results are recorded on Tables 2 and 3. As seen in Table 2, the impact energy (reported as total energy) of the notched samples decreased significantly to approximately 25% of the unreinforced material of Example 1. Table 3 illustrates that the impact energy (reported as total energy) of the unnotched samples dropped significantly to approximately 6% of that of the unreinforced material of Example 1.

The reinforced material of Example 2 had an significant increase in modulus of elasticity over the unreinforced material of Example 1 but the toughness of the material of Example 2 was reduced. What is needed is a material with the improved modulus of elasticity that does not suffer from the dramatic reduction in toughness.

Table 2

NOTCHED IMPACT TESTING

Sample Number	Orientation	Maximum Load (kN)	Total Energy (J)	Total Deflection*
1		10.23	6.56	1.75
2		5.41	1.61	0.9
3	Arrestor	10.31	17.15	8.20
3	Divider	6.39	3.88	1.30
4	Arrestor	10.74	22.71	10.00
4	Divider	7.27	3.92	1.20
5	Arrestor	7.48	7.59	5.00
5	Divider	5.89	2.82	0.90

* mm

Table 3

UNNOTCHED IMPACT TESTING

Sample Number	Orientation	Maximum Load (kN)	Total Energy (J)	Total Deflection*
1			100.00	
2			5.98	
3	Arrestor		46.78	
3	Divider		38.81	
4	Arrestor		47.46	
4	Divider		34.12	
5	Arrestor		28.48	
5	Divider		15.13	

* mm

Example 3

Material from Examples 1 and 2 were each rolled to a plate thickness of approximately 0.5 inches and trimmed. A three layer laminate formed from two layers of the unreinforced material of Example 1 surrounding the reinforced material of Example 2 were produced by first etching the surfaces with a solution of sodium hydroxide and mechanically abrading the bonding surfaces. The layers were then stacked, held together with a spot weld and preheated to approximately 850°F. The heated stack was then passed through the nip of rollers and reduced approximately 15% per pass for three passes to form the laminate.

The elastic modulus, yield strength (YS) and strain at failure were then measured and recorded on Table 1. As can be seen in Table 1, the laminated material of Example 3 exhibited a 36% increase in modulus of elasticity over the material of Example 1 and the yield strength remained about the same (2% increase).

Charpy impact tests were performed on

notched and unnotched laminates of the material of Example 3 and the results are recorded on Tables 2 and 3. Surprisingly, the impact energy (reported as total energy) of the notched samples exhibited an increase in toughness in the crack arrestor orientation (see Figure 2) of approximately 261% of the unreinforced material of Example 1 and an increase of over 1000% of the reinforced material of Example 2.

Table 3 illustrates that the drop in toughness or impact energy (reported as total energy) of the unnotched laminates of Example 3 was significantly less than the reinforced material of Example 2. The toughness of the unnotched material of Example 3 was over 600% higher than the reinforced material of Example 2 in both the crack arrestor and crack divider orientations.

Figure 1 illustrates the crack blunting and interface delamination of the material of Example 3. As explained above, it is believed that the crack blunting and interface delamination lead to the materials high fracture toughness. The combination of high modulus of elasticity and high toughness (in arrestor orientation) of the laminated material of Example 3 is unexpected and will be more useful in aircraft applications such as wings, fuselage and tail sections than either the reinforced or unreinforced X7093 alone.

Example 4

The procedure of Example 3 was repeated except that a layer of aluminum foil (A 1100 alloy) was placed between the unreinforced and reinforced alloys. The elastic modulus, yield strength (YS) and strain at failure were then measured and recorded on Table 1. As can

be seen in Table 1, the laminated material of Example 4 exhibited a 22% increase in modulus of elasticity over the material of Example 1.

Charpy impact tests were performed on notched and unnotched laminates of the material of Example 4 and the results are recorded on Tables 2 and 3. Surprisingly, the impact energy (reported as total energy) of the notched samples exhibited an increase in toughness in the crack arrestor orientation of approximately 340% of the unreinforced material of Example 1 and an increase of over 1400% of the reinforced material of Example 2. Unexpectedly, the use of the foil interlayer in the laminate of Example 4 produced an increase in impact energy that was greater than that of the laminate formed without foil (Example 3).

Table 3 illustrates that the drop in toughness or impact energy (reported as total energy) of the unnotched laminate of Example 4 was significantly less than the reinforced material of Example 2. The toughness of the unnotched material of Example 4 was over 600% higher than the reinforced material of Example 2 in both the crack arrestor and crack divider orientations. The combination of high modulus of elasticity and high toughness (in arrestor orientation) of the laminated material of Example 4 is unexpected and will be more useful in aircraft applications such as wings, fuselage and tail sections than either the reinforced or unreinforced X7093 alone.

<u>Example 5</u>

The procedure of Example 3 was repeated except that the laminate was adhesively bonded instead of roll bonded. The adhesive bonding was accomplished by applying a layer of

epoxy to the bonding surfaces after etching. AF1632K epoxy which is commerically available from 3M corporation is suitable for use as an adhesive. After the adhesive is applied the stack is formed as in Example 3. The stack is held at approximately 70 psi and 250°F. for one hour to cure the epoxy.

The elastic modulus, yield strength (YS) and strain at failure were then measured and recorded on Table 1. As can be seen in Table 1, the laminated material of Example 5 exhibited a 16% increase in modulus of elasticity over the material of Example 1.

Charpy impact tests were performed on notched and unnotched laminates of the material of Example 4 and the results are recorded on Tables 2 and 3. Surprisingly, the impact energy (reported as total energy) of the notched samples exhibited an increase in toughness in the crack arrestor orientation of approximately 115% of the unreinforced material of Example 1 and an increase of over 470% of the reinforced material of Example 2.

Table 3 illustrates that the drop in toughness or impact energy (reported as total energy) of the unnotched laminate of Example 5 was significantly less than the reinforced material of Example 2. The toughness of the unnotched material of Example 3 was over 450% higher than the reinforced material of Example 2 in the crack arrestor orientation. The combination of high modulus of elasticity and high toughness (in arrestor orientation) of the laminated material of Example 5 is unexpected and will be more useful in aircraft applications such as wings, fuselage and tail sections than either the reinforced or unreinforced X7093

alone.

It is to be appreciated that certain features of the present invention may be changed without departing from the present invention. Thus, for example, although the invention was described in terms of silicon carbide reinforcement material, other reinforcement materials known in the art may also be used. In general, these include a wide variety of oxides, carbides and nitrides. Specifically, titanium carbide, boron carbide, graphite, carbon, alumina, silicon nitride, aluminum nitride, mullite, titanium boride, zirconium boride, silicon aluminum oxynitride (SiAlON) and combinations thereof can also be used as reinforcement material.

In addition, while the invention has referred generally to powders, it should be understood that other methods may be used to form the reinforced metal component of the laminate. Other methods include spray forming, plasma spraying, die casting, pressure casting, rheocasting and compocasting.

While the invention has been described terms of forming a three layer laminate from materials having thicknesses of the same order of magnitude, the invention is not necessarily limited thereto. For example, the laminate may be formed from any number of layers. It is expected that laminates of five or seven layers will be found to be useful in the art. If more than one reinforced layer is used to form the composite it is not necessary that they all contain the same volume percent of reinforcement material. In addition, it is not necessary that the layers in the stack alternate between reinforced and unreinforced material. For

example, the laminate may be formed from five of layers with the first and fifth layers being fabricated from unreinforced material and the second and forth layers fabricated from a material containing 8 vol.% reinforcement and the middle or third layer containing 18 vol.% reinforcement. Furthermore, it is contemplated that some of the layers may have a thickness which is substantially thinner than others and yet still thicker than foil.

In addition, while the invention has referred generally to forming laminates from separate and distinct layers of compositionally homogeneous flat rolled product, it should be understood that the laminate of the present invention is not so limited. Each layer of material to be used in the laminate may be formed from spray forming or plasma spraying technique in which the amount of the reinforcement is varied as the metal product is being deposited. Thus, the volume percent of reinforcement material may be varied across the thickness of the reinforcement layer. This variation in volume percent may be abrupt or gradual depending on the desired outcome. In addition, it is contemplated that the entire laminate may be formed by changing the alternating the volume percent of particulate material from below 5 vol.% to above 5 vol.% and thereby form the dual structure (unreinforced and reinforced layers) with a single spraying. Similarly, the composition of the alloy that is being deposited may be varied within each layer or the entire structure. In addition, it is contemplated that each layer need not extend the entire length or width of the product.

While the invention has been described

terms of roll bonding and adhesive bonding, it will be understood that the basic invention is not necessarily limited thereto. For example, layers may be laminated by explosive bonding, difussion bonding, extruding and other bonding techniques known in the art.

Furthermore, while the invention has been described in part with respect to aluminum and its alloys, it will be understood that the invention is not necessarily limited thereto. For example, the dual structure effect has application to other metal structures such as steel, titanium and other alloys, and such is contemplated within the purview of the invention.

Whereas the preferred embodiments of the present invention have been described above in terms of being especially valuable in producing X7093 aluminum alloy parts, it will be apparent to those skilled in the art that the present invention will also be valuable producing laminated composites made of other aluminum alloys containing about 80 percent or more by weight of aluminum and one or more alloying elements. Among such suitable alloying elements is at least one element selected from the group of essentially character forming alloying elements and consisting of manganese, zinc, beryllium, lithium, copper, silicon and magnesium. I term these alloying elements as essentially character forming for the reason that the contemplated alloys containing one or more of them essentially derive their characteristic properties from such elements. Usually the amounts of each of the elements which impart such characteristics are, as to each of magnesium and copper, about 0.5 to about

10 wt.% of the total alloy if the element is present as an alloying element in the alloy; as to the element zinc, about 0.05 to about 12.0% of the total alloy if such element is present as an alloying element; as to the element beryllium, about 0.001 to about 5.0% of the total alloy if such element is present as an alloying element; as to the element lithium, about 0.2 to about 3.0% of the total alloy if such element is present as an alloying element; and as to the element manganese, if it is present as an alloying element, usually about 0.15 to about 2.0% of the total alloy.

The elements iron and silicon, while perhaps not entirely or always accurately classifiable as essentially character forming alloy elements, are often present in aluminum alloy in appreciable quantities and can have a marked effect upon the derived characteristic properties of certain alloys containing the same. Iron, for example, which if often present and considered as an undesired impurity, is oftentimes desirably present and adjusted in amounts of about 0.3 to 2.0 wt.% of the total alloy to perform specific functions. Silicon may also be so considered, and while found in a range varying from about 0.25 to as much as 15%, is more often desirably found in the range of about 0.3 to 1.5% to perform specific functions. In light of the foregoing dual nature of these elements and for convenience of definition, the elements iron and silicon may, at least when desirably present in character affecting amounts in certain alloys, be properly also considered as character forming alloying ingredients.

Such aluminum and aluminum alloys, which may contain one or more of these essential

character forming elements, may contain, either with or without the aforementioned character forming elements, quantities of certain well known ancillary alloying elements for the purpose of enhancing particular properties. Such ancillary elements are usually chromium, nickel, zirconium, vanadium, titanium, boron, lead, cadmium, bismuth, and occasionally silicon and iron. Also, while lithium is listed above an essential character forming element, it may in some instances occur in an alloy as an ancillary element in an amount within the range outlined above. When one of these ancillary elements is present in the aluminum alloy of the type herein contemplated, the amount, in terms of percent by weight of the total alloy, varies with the element in question but is usually about 0.05 to 0.4%, titanium about 0.01 to 0.25%, vanadium or zirconium about 0.05 to 0.25%, boron about 0.0002 to 0.04%, cadmium about 0.05 to 0.5%, and bismuth or lead about 0.4 to 0.7%.

The aluminum alloys included most preferably the wrought and forged aluminum alloys such as those registered with the Aluminum Association by the designations 2014, 2017, 2117, 2618, 2219, 2419, 2024, 2124, 2224, 2036, 6101, 6201, 6009, 6010, 6151, 6351, 6951, 6053, 6061, 6262, 6063, 6066, 6070, 7001, 7005, 7016, 7021, 7029, 7049, 7050, X7093, 7150, 7075, 7175(b), 7475, 7076, 7178 and other appropriate alloys of similar designation. Of particular interest are the aluminum alloys X2080, 6113, X7093. These aluminum alloys generally include the generic designation 2000 series alloys, 6000 series alloys and 7000 series alloys. The cast alloys treatable by the present invention

include most preferably the cast aluminum alloys, such as those designated 222, 242, 295, 296, 319, 336, 355, 356, and 712. These cast alloys generally have the generic designation 200 series alloys, 600 series alloys and 700 series alloys.

These and other changes of the type described could be made to the present invention without departing from the spirit of the invention. The scope of the present invention is indicated by the broad general meaning of the terms in which the claims are expressed.

CLAIMS

1. A laminated metal matrix composite comprising a laminated stack of alternate layers of unreinforced metal and reinforced metal.

2. The metal matrix composite of claim 1, in which the thickness of said unreinforced layers are of the same order of magnitude as said reinforced layers.

3. The metal matrix composite of claim 1, in which said unreinforced layers and said reinforced layers have a thickness greater than about 0.5 mm.

4. The metal matrix composite of claim 1, in which said unreinforced metal is an alloy of a metal selected from the group consisting of aluminum, copper, iron, titanium, magnesium and zinc.

5. The metal matrix composite of claim 1, in which said unreinforced metal is an aluminum alloy.

6. The metal matrix composite of claim 1, in which said reinforced metal is an alloy of a metal selected from the group consisting of aluminum, copper, iron, titanium, magnesium and zinc.

7. The metal matrix composite of claim 1, in which said reinforced metal is an aluminum alloy containing at least 5 vol.% of reinforcing material.

8. The metal matrix composite of claim 1, in which said reinforced metal contain particles selected from the group consisting of boron carbide, silicon carbide, silicon nitride, graphite, alumina, titanium carbide, carbon, silicon nitride, aluminum nitride, mullite, titanium boride, zirconium boride, silicon aluminum oxynitride (SiAlON) and combinations

thereof.

9. The metal matrix composite of claim 1, in which said reinforced metal contain particles of silicon carbide.

10. The metal matrix composite of claim 1, in which said reinforced metal contain particles of silicon carbide having an average particle size of less than about 50 microns.

11. The metal matrix composite of claim 1, in which said unreinforced metal and said reinforced metal are formed from different alloys.

12. The metal matrix composite of claim 1, in which said unreinforced metal and said reinforced metal are formed from different aluminum alloys.

13. The metal matrix composite of claim 1, in which metal foil is interlayered between said unreinforced metal and said reinforced metal.

14. An aircraft tail section or empennage which is at least partly formed from the laminated metal matrix composite of claim 1.

15. An aircraft wing which is at least partly formed from the laminated metal matrix composite of claim 1.

16. An aircraft wing comprising a plurality of laminated panels of layers of unreinforced and reinforced aluminaum alloy.

17. An aircraft tail section comprising a plurality of laminated panels of layers of unreinforced aluminum alloy and the same aluminum alloy having 5 to 55 vol.% of particulate material of silicon carbide.

18. An aircraft wing or section thereof comprising a plurality of laminated panels of layers of unreinforced aluminum alloy and the same aluminum alloy having 5 to 55 vol.% of

particulate material of silicon carbide.

19. A method for producing a metal matrix composite having increased combination of elastic modulus and fracture toughness, said method comprising the steps of:

(a) providing a plurality of layers of unreinforced metal and reinforced metal;

(b) stacking said layers; and

(c) applying sufficient heat pressure to said stack to cause interlayer adhesion of said layers.

20. The method of claim 19, in which step (a) further includes:

said stack of layers comprises alternate layers of unreinforced metal and reinforced metal.

21. The method of claim 19, in which step (a) further includes:

said stack of layers comprises alternate layers of unreinforced aluminum alloy and reinforced aluminum alloy.

22. The method of claim 19 in which step (a) further includes:

said stack of layers comprises alternate layers of unreinforced metal and metal which has been reinforced with particles selected from the group consisting of boron carbide, silicon carbide, silicon nitride, graphite, alumina, titanium carbide, carbon, silicon nitride, aluminum nitride, mullite, titanium boride, zirconium boride, silicon aluminum oxynitride (SiAlON) and combinations thereof.

23. The method of claim 19, in which comprises:

roll bonding said stack of layers to form a consolidated product.

24. The method of claim 19, in which step (b) further includes:

adhesively bonding said stack of layers to form a consolidated product.

25. A method of producing an aluminum alloy having a combination of improved fracture toughness and elastic modulus, said method comprising the steps of:

(a) providing a first aluminum powder alloy;

(b) admixing with said first aluminum powder alloy a reinforcement material to provide a blend;

(c) pressing the blend to make a green compact;

(d) hot pressing said green compact;

(e) working the hot pressed compact to produce a first product flat rolled product;

(f) providing a second flat rolled aluminum alloy product;

(g) stacking said first and second products to form at least three alternating layers; and

(h) laminating said stack.

26. The method of claim 25, in which further includes:

heat treating said stack.

27. The method of claim 25, in which said first and second flat rolled products are formed from the same aluminum alloy.

28. The method in accordance with claim 25, wherein said reinforcing material is at least 5 vol. % of the blend.

29. The method in accordance with claim 25, further including the step of vacuum preheating the green compact for purposes of degassing.

30. The method in accordance with claim 25, further including the step of heat treating said stack at a temperature in the range of 800° to 1100°F.

31. The method in accordance with claim 30, including the step of aging the product after the heat treating step.

32. The method in accordance with claim 25, including the step of artificial aging said stack at a temperature of 200° to 400°F.

33. The method in accordance with claim 25, in which step (h) includes roll bonding said stack to form a consolidated product.

34. The method in accordance with claim 25, in which step (h) includes adhesively bonding said stack to form a consolidated product.

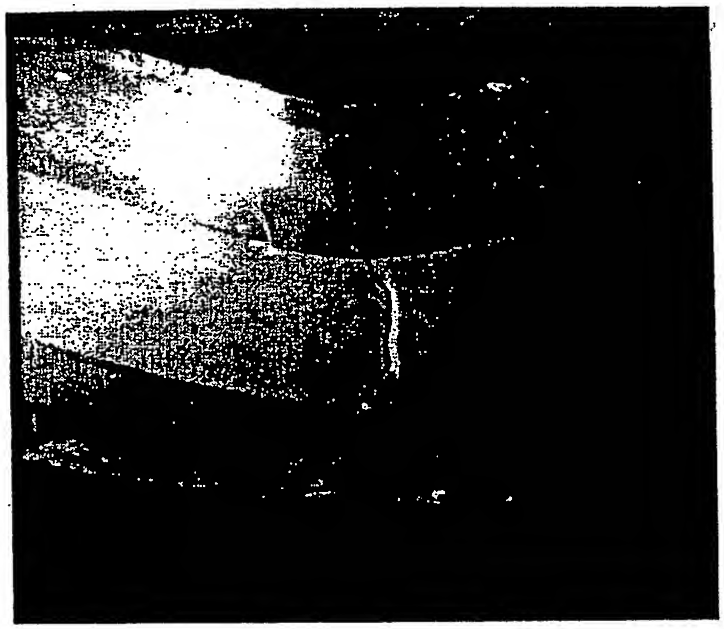

FIG. 1

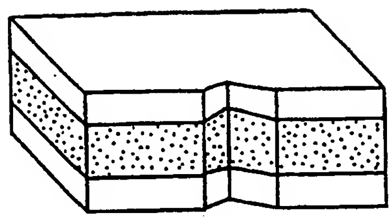

FIG. 2A

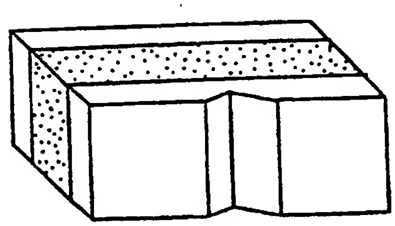

FIG. 2B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/10360

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :C22C 1/09, 1/10; B32B 15/00; B22F 7/02
US CL : 428/614, 654; 244/133; 419/5, 6, 8; 228/190; 156/89
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 428/614, 654; 244/133; 419/5, 6, 8; 228/190; 156/89; 428/608; 244/123, 117R; 29/419.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Kirk-Othmer

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS : laminate and aluminum, adhesive or roll bonding.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 4,753,850 (Ibe et al) 28 June 1988, abstract, Figure 3, column 1, lines 52-55, column 2, lines 54-56, column 3, lines 30-34.	1, 4-6, 12
Y	US, A, 4,197,360 (Throop) 8 April 1980, abstract, claims 1, 5, column 2, lines 53-61, column 7, lines 1-2	1-12, 14-34
Y	US, 4,973,522 (Jordan et al) 27 November 1990, abstract, claims 1-4	1-12, 14-34
Y	US, A, 4,999,061 (Curtis et al) 12 March 1991, column 1.	1-12, 14-34

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 January 1994	FEB 08 1994

Name and mailing address of the ISA/US	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/10360

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 3,245,782 (Ray) 12 April 1966, Figure 1, column 1, lines 25-28, column 5, lines 18-24	19-34
X	US, A, 4,045,857 (Suzuki) 6 September 1977, abstract, Figure 3, column 4, lines 37-56, column 5, lines 3-4	1, 4-12, 14-18
A	JP, A, 52-011,134 (Mitsubishi Heavy Ind KK) 17 July 1975, abstract	1

INTERNATIONAL SEARCH REPORT

International application No. PCT/US93/10360

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING

This ISA found multiple inventions as follows:

Group I. Claims 1-12, 19-22, 25-32, 23, 33, drawn to an Al or Al alloy next to Al or Al alloy (Al/Al) product and method of making by roll bonding.

Group Ia. Claims 1-12, 19-22, 25-32, 24, 34, drawn to an Al/Al product and method of making by adhesive bonding.

Group II. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Cu product and a method of making by roll bonding.

Group IIa. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Cu product and a method of making by adhesive bonding.

Group III. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Fe product and a method of making by roll bonding.

Group IIIa. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Fe product and a method of making by adhesive bonding.

Group IV. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Ti product and a method of making by roll bonding.

Group IVa. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Ti product and a method of making by adhesive bonding.

Group V. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Mg product and a method of making by roll bonding.Group Va. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Mg product and a method of making by adhesive bonding.

Group VI. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Zn product and a method of making by roll bonding.

Group VIa. Claims 1-4, 6, 8-10, 19-20, drawn to an Al/Zn product and a method of making by adhesive bonding.

Group VII. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Cu product and a method of making by roll bonding.

Group VIIa. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Cu product and a method of making by adhesive bonding.

Group VIII. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Fe product and a method of making by roll bonding.

Group VIIIa. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Fe product and a method of making by adhesive bonding.

Group IX. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Ti product and a method of making by roll bonding.

Group IXa. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Ti product and a method of making by adhesive bonding.Group X. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Mg product and a method of making by roll bonding.

Group Xa. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Mg product and a method of making by adhesive bonding.

Group XI. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Zn product and a method of making by roll bonding.

Group XIa. Claims 1-4, 6, 8-10, 19-20, drawn to a Cu/Zn product and a method of making by adhesive bonding.

Group XII. Claims 1-4, 6, 8-10, 19-20, drawn to a Fe/Fe product and a method of making by roll bonding.

Group XIIa. Claims 1-4, 6, 8-10, 19-20, drawn to a Fe/Fe product and a method of making by adhesive bonding.

Group XIII. Claims 1-4, 6, 8-10, 19-20, drawn to a Fe/Ti product and a method of making by roll bonding.

Group XIIIa. Claims 1-4, 6, 8-10, 19-20, drawn to a Fe/Ti product and a method of making by adhesive bonding.

Group XIV. Claims 1-4, 6, 8-10, 19-20, drawn to a Fe/Mg product and a method of making by roll bonding.Group XIVa. Claims 1-4, 6, 8-10, 19-20, drawn to a Fe/Mg product and a method of making by adhesive bonding.

Group XV. Claims 1-4, 6, 8-10, 19-20, drawn to a Fe/Zn product and a method of making by roll bonding.

Group XVa. Claims 1-4, 6, 8-10, 19-20, drawn to a Fe/Zn product and a method of making by adhesive bonding.

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Group XVI. Claims 1-4, 6, 8-10, 19-20, drawn to a Ti/Ti product and a method of making by roll bonding.

Group XVIa. Claims 1-4, 6, 8-10, 19-20, drawn to a Ti/Ti product and a method of making by adhesive bonding.

Group XVII. Claims 1-4, 6, 8-10, 19-20, drawn to a Ti/Mg product and a method of making by roll bonding.

Group XVIIa. Claims 1-4, 6, 8-10, 19-20, drawn to a Ti/Mg product and a method of making by adhesive bonding.

Group XVIII. Claims 1-4, 6, 8-10, 19-20, drawn to a Ti/Zn product and a method of making by roll bonding.

Group XVIIIa. Claims 1-4, 6, 8-10, 19-20, drawn to a Ti/Zn product and a method of making by adhesive bonding.Group XIX. Claims 1-4, 6, 8-10, 19-20, drawn to a Mg/Mg product and a method of making by roll bonding.

Group XIXa. Claims 1-4, 6, 8-10, 19-20, drawn to a Mg/Mg product and a method of making by adhesive bonding.

Group XX. Claims 1-4, 6, 8-10, 19-20, drawn to a Mg/Zn product and a method of making by roll bonding.

Group XXa. Claims 1-4, 6, 8-10, 19-20, drawn to a Mg/Zn product and a method of making by adhesive bonding.

Group XXI. Claims 1-4, 6, 8-10, 19-20, drawn to a Zn/Zn product and a method of making by roll bonding.

Group XXIa. Claims 1-4, 6, 8-10, 19-20, drawn to a Zn/Zn product and a method of making by adhesive bonding.

Group XXII. Claims 1-3, 13, drawn to a product including a metal foil interlayer between the metal and reinforced metal.

Group XXIII. Claims 1-7, 14-18, drawn to an aircraft part.

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